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Abstract

A total of ten acoustic grenade soundings were carried out from Kronogard, Sweden (66N) and Barrow, Alaska (71N) during the summers of 1963 through 1965 to determine the relationship between temperature structure in the atmosphere and the occurrence of noctilucent clouds. The results of the observations at Barrow display remarkable uniformity with temperature variations generally on the order of 3 to 4K from sounding to sounding at any given altitude throughout the mesosphere. Extremely cold mesopause temperatures ranging from 132 to 140K and steep uniform mesospheric lapse rates were observed in all of the soundings. Soundings were made alternately with and without noctilucent cloud displays within a period of less than 48 hours. No significant difference in the temperature structure was noted between the presence and absence of clouds.

Of the six soundings conducted at Kronogard, four were carried out during noctilucent cloud displays and two served as control soundings. Here again, the mesopause temperatures ranged from 130 to 148K and no significant difference in the mesopause temperature was observed between the cloud and no-cloud categories.

The seasonal temperature variations in the mesosphere at high latitudes are believed to result from a meridional circulation in the upper atmosphere which also provides a mechanism for the transport of water vapor from the troposphere to the high latitude summer mesosphere. Supersaturation by small amounts of water vapor is quite feasible in the narrow layer near the mesopause

where these extremely cold temperatures were observed and freezing would undoubtedly occur with the introduction of sublimation nuclei into this region. These results lead to the conclusion that noctilucent clouds are composed of particles which grow, by a process of sublimation, to sufficient size to scatter sunlight as they fall through or are suspended in the low temperature mesopause and that a mesopause temperature of less than 140 to 150K is a necessary but not sufficient condition for the existence of noctilucent clouds.

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1. Introduction

Noctilucent clouds have been the subject of scientific interest for many years because of the great heights above the earth at which they occur. The clouds have generally been observed at altitudes ranging from 78 to 90 km with the majority of observations indicating a cloud height of about 83 km (Fogle, 1966). These clouds have been sighted only at high latitudes and there most frequently during the four to six week period following the summer solstice. Noctilucent clouds are visible only during the time when the sun is below the observer's horizon and the clouds are directly illuminated by sunlight against a darkened sky background. The high latitudes provide favorable geometry for observation of the clouds for considerably longer periods each day than the middle and low latitudes, but there is strong evidence that noctilucent clouds appear only at high latitudes in summer and not at all at middle or low latitudes (Fogle, 1966). The fact that the clouds exist only at high latitudes and only during summer can be explained in terms of the temperature structure of the mesosphere at these latitudes.

The acoustic grenade technique provided measurements of atmospheric temperature, pressure, density and wind profiles as high as the noctilucent cloud region for the first time. A total of ten grenade soundings were carried out from Kronogard, Sweden (66N) and Barrow, Alaska (71N) during the summers of 1963 through 1965 to determine the relationship between the mesospheric temperature structure and the occurrence of noctilucent clouds. The soundings at Kronogard were conducted under a cooperative program between NASA and the Swedish Space Committee.

2. Results and discussion

The results of the Barrow temperature soundings made in August 1965, are given in Figure 1. These profiles display remarkable uniformity with temperature variations generally on the order of 3 to 4K from sounding to sounding throughout the mesosphere. The mesopause temperatures ranged from 132 to 140K and the steep uniform lapse rate typical of the high latitude summer mesosphere was observed in all the soundings. The series of four soundings was initiated during a noctilucent cloud display and completed almost 48 hours later during the confirmed absence of the clouds. The second and third soundings were made during daylight and were intended only to obtain continuity. No significant difference in the temperature structure can be seen between the soundings made in the presence and absence of noctilucent clouds. There is almost no diurnal temperature variation in these profiles. This is not surprising because the upper atmosphere at Barrow is exposed to almost continuous sunlight during early August and the solar elevation angle at 50 km, for example, varies only from 30 degrees at noon to 6 degrees at midnight.

The same situation is evident in Figure 2 which shows the noctilucent cloud and control soundings at Barrow along with a similar pair of soundings made almost 72 hours apart at Kronogard in 1963. The first sounding at each site was launched during a noctilucent cloud display and the second sounding served as a control sounding, having been carried out in the confirmed absence of the clouds. In the Barrow case, the minimum temperature of the profile made in the presence of noctilucent clouds was 139K, 3K warmer than the mesopause temperature of the control sounding. In the Kronogard case, however, the minimum temperature of the profile made during the cloud display was 130K, 18K colder than the mesopause temperature of the control sounding.

Figure 3 shows average temperature profiles for the five soundings conducted during noctilucent cloud displays (solid curve) and the three soundings conducted during the confirmed absence of noctilucent clouds (dashed curve). The curves do not differ by more than 5K at any point between 45 and 90 km. The warm stratopause, the steep uniform lapse rate and the extremely cold mesopause are essentially identical for both profiles. The brackets indicate the range of temperatures included in the averages at the altitudes shown. Included in the five soundings conducted during noctilucent cloud displays were mesopause temperatures which varied from 130 to 147K. In the soundings conducted during the absence of the clouds, the mesopause temperatures ranged from 129 to 149K. Thus it can be seen that the coldest temperatures did not necessarily produce noctilucent clouds but the clouds were always accompanied by mesopause temperatures less than 140 to 150K.

There exist two schools of thought concerning the composition of noctilucent cloud particles. One theory assumes the presence of sufficient water vapor at the mesopause to form ice coatings on dust particles which serve as condensation nuclei (Ludlam, 1957). The other theory does not accept the presence of water vapor and ice coatings, but explains the noctilucent clouds in terms of the light scattering properties of the dust alone (Diermendjian and Vestine, 1959). In both cases the dust is believed to originate from the vaporization of incoming meteors. Sampling experiments such as those discussed by Hemenway et al. (1964) and Hemenway, Soberman and Witt (1964) have been conducted to resolve the question of the cloud particle composition, and traces of a volatile substance believed to be ice were found surrounding many of the larger particles obtained from a noctilucent cloud.

It is believed, in view of the temperature results reported above, that the occurrence of noctilucent clouds depends largely on the amount of water vapor present at the mesopause assuming that the optical geometry, the dust nuclei and the cold mesopause typical of the high latitude summer atmosphere exist. (Though, in fact, these conditions also may vary considerably in both space and time.) Khvostikov (1966) has postulated that "Noctilucent clouds appear in the atmosphere at the place and the time where and when the temperature of the air turns out to be low enough." But a given low temperature alone is not sufficient to produce noctilucent clouds unless the low temperature occurs in conjunction with sufficient water vapor. Thus the variation of the water vapor content of the high atmosphere must be considered.

Seasonal variations of the mesopause temperature produce not only sufficiently cold conditions for the formation of noctilucent clouds, but also provide a circulation consistent with the transport of water vapor to the mesopause at high latitudes in summer. Nordberg and Stroud (1961) reported the high latitude summertime mesopause to be almost 80K colder than the wintertime mesopause. This result is confirmed by the average temperature profiles for summer and winter at high latitudes given in Figure 4. The solid curve represents the average of 11 winter soundings conducted at Churchill (59N) and Barrow between 1962 and 1965. The dashed curve represents the average of 15 summer soundings conducted at Churchill, Barrow and Kronogard between 1962 and 1965 and includes the 10 soundings from Barrow and Kronogard discussed earlier. Such results are not in agreement with what one would expect from purely radiative considerations since at high latitudes, the summer mesosphere is heated almost 24 hours a day and the winter mesosphere is dark almost 24 hours a day. Leovy (1964) demonstrated that a meridional circulation superimposed on an atmosphere in radiative equilibrium gave good qualitative agreement with the observed seasonal temperature variations. This meridional circulation caused ascending motion at the summer pole and descending motion at the winter pole, thereby transferring heat from the radiatively heated summer upper atmosphere to the heat deficient winter upper atmosphere. Hesstvedt (1964) used a similar meridional circulation proposed earlier by Murgatroyd and Singleton to explain the presence of water vapor in the upper atmosphere. This model is also consistent with the observed temperature variations. As can be seen in Figure 5, Hesstvedt's model shows that the source of the water vapor is the tropical troposphere and that the water vapor enters the stratosphere through the gap in the tropopause. From this relatively narrow latitudinal band near the equator, air rises to 25 km altitude, moves meridionally toward the summer pole and then ascends rapidly at high latitudes. Poleward of 60 degrees latitude in the summer hemisphere, air at 80 km is seen to originate from the equatorial troposphere. Such a model qualitatively explains both the mechanisms for transporting water vapor to the summer mesopause and for transferring heat from the summer mesosphere to the winter mesosphere, thereby accounting for the observed seasonal variations in the temperature structure.

There is no more reason to believe that water vapor is homogeneously distributed in the high latitude mesosphere than to believe that such a situation exists in the troposphere. The meridional circulation shown in Figure 5 represents the average motion in the stratosphere and mesosphere but this circulation is subject to frequent and dynamic changes and therefore any assumption of steady state flow or homogeneous composition is unrealistic. Thus the low temperatures at the mesopause may not cause noctilucent clouds if there is insufficient water vapor available. The questions of how much water vapor is available and the magnitude of the vertical velocities necessary to transport the water vapor to the mesopause must remain unanswered for the present since no in situ measurements have been made to confirm or to refute the estimates and extrapolations which various authors have published. As can be seen in Figure 6, Hesstvedt (1962) had estimated the mixing ratio at the mesopause to be 1g kg^{-1}

which resulted in a frost point of 172K at 82 km. Hesstvedt (1964) later revised this value downward to the order of 10^{-2}g kg^{-1} which is in reasonable agreement with Paton's (1964) estimate of 6×10^{-3}g kg^{-1} corresponding to a frost point of 150K at 80 km. Charlson (1965) used the 130K temperature measured at Kronogard as a conservative approximation to develop a steady state model for noctilucent clouds. Thus the estimates of water vapor content at the mesopause have grown smaller as the estimates and observations of mesopause temperatures have become lower.

Figure 6 also compares the frost points for various mixing ratios and a curve which has been extrapolated from measurements at altitudes reached by balloon borne instrumentation with the average temperature profile for the five soundings made during noctilucent cloud displays. Curves A, B and C were computed for constant mixing ratios using the average pressure profile derived from the average measured high latitude summertime temperature profile given in Figure 4. Curve A gives the frost points for a mixing ratio of 10^{-3}g kg^{-1}, curve B for 10^{-2}g kg^{-1} and curve C for 10^{-1}g kg^{-1}. Badinov et al. (1966) have extrapolated frost point values from measurements made by various techniques at balloon altitudes of 28 to 30 km. Badinov's results are given by curve D and are based on a mixing ratio measured in the stratosphere which he believes stabilizes with height to a value on the order of 10^{-3}g kg^{-1}. The average temperature profile for the five noctilucent cloud soundings is given by curve E in Figure 6. The mesopause temperature of 143K corresponds to a saturation mixing ratio of approximately 1.3×10^{-3}g kg^{-1}. It must be remembered, however, that this is an average value of the mixing ratio and that both colder and warmer temperatures, corresponding to lower and higher saturation mixing ratios have been measured during the cloud displays.

3. Summary and conclusions

Since no significant difference in the observed temperature structure was noted between those soundings conducted in the presence of noctilucent clouds and those conducted in the absence of the clouds, it is concluded that a mesopause temperature of less than 140 to 150K is a necessary but not sufficient condition for the existence of noctilucent clouds. The variation of the water vapor content at the mesopause is believed to be a key factor in the occurrence of the clouds. In view of the circulation which is implied by the seasonal temperature differences in the mesosphere, small amounts of water vapor are believed to be transported by this circulation into the mesosphere during the summer at high latitudes. There saturation or supersaturation occurs in the narrow layer at the mesopause where these extremely cold temperatures are observed. Dust particles, originating from incoming meteors, are believed to serve as sublimation nuclei in this saturated region and thereby grow to sufficient size to scatter sunlight, producing noctilucent clouds.

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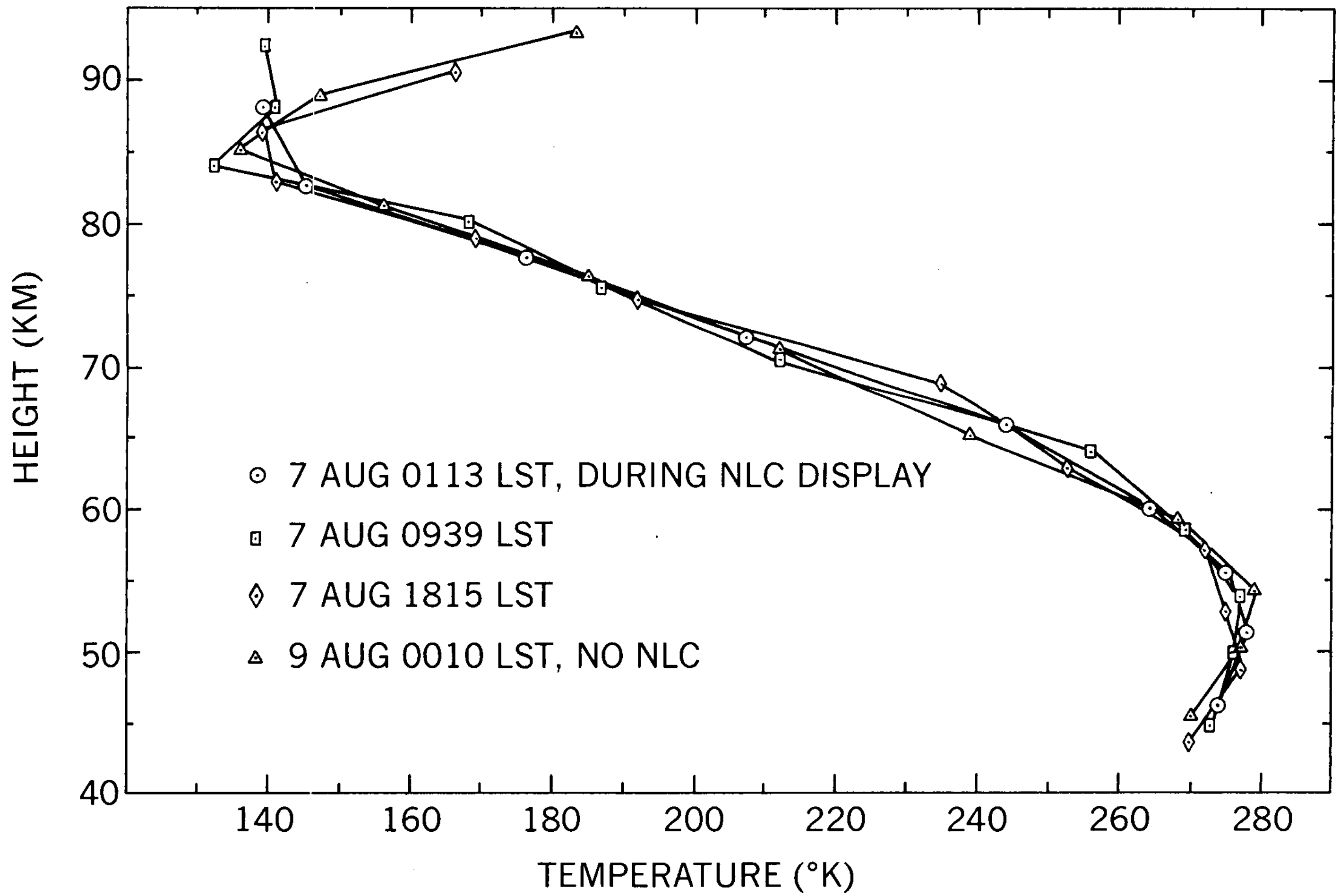

Figure 1. Temperature profiles above Barrow, Alaska (71N) during August, 1965.

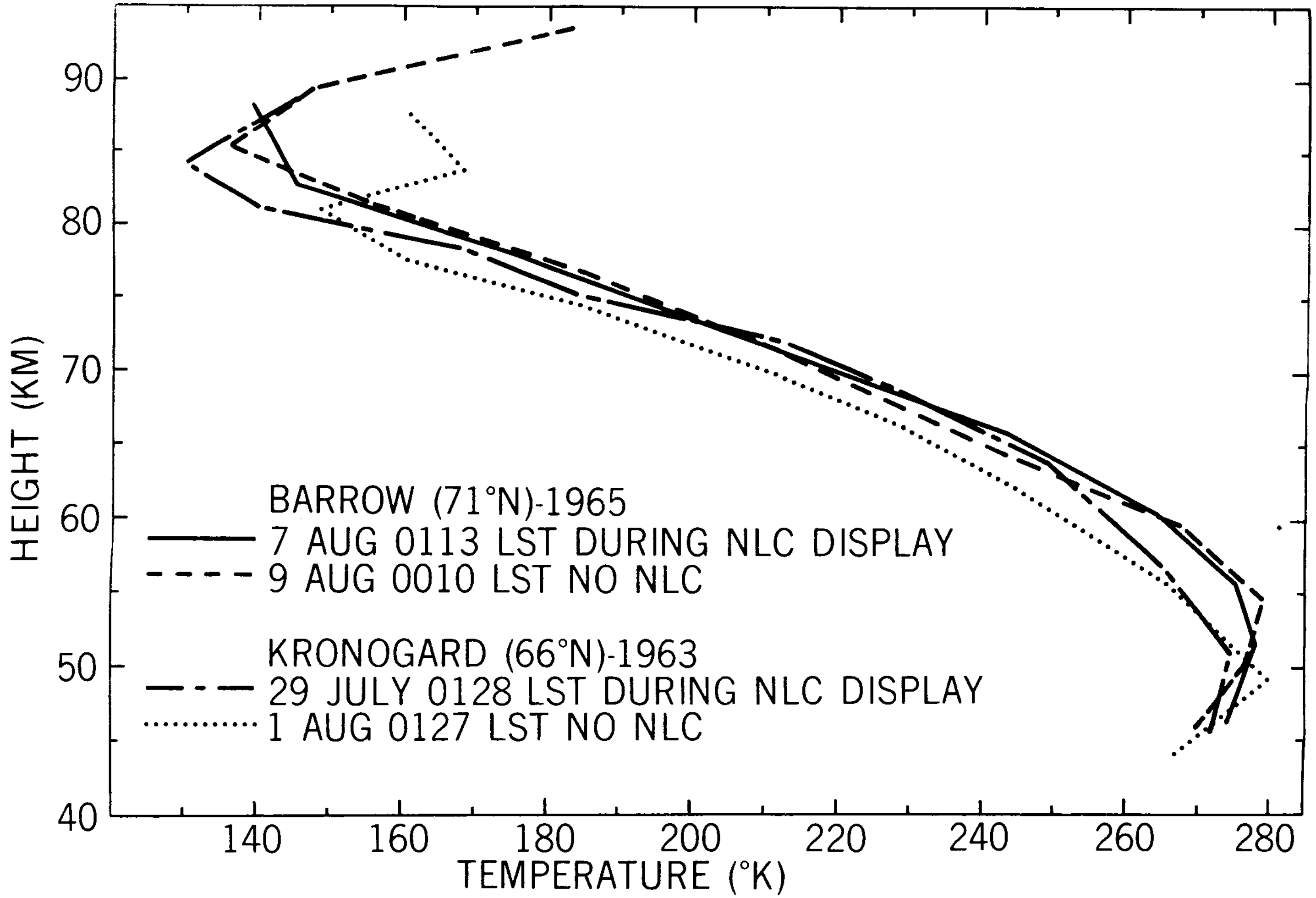

Figure 2. Temperature profiles above Kronogard, Sweden (66N) and Barrow during the summers of 1963 and 1965, respectively. Note that the Barrow mesopause was colder in the absence of noctilucent clouds than during the cloud display, but the reverse was observed at Kronogard.

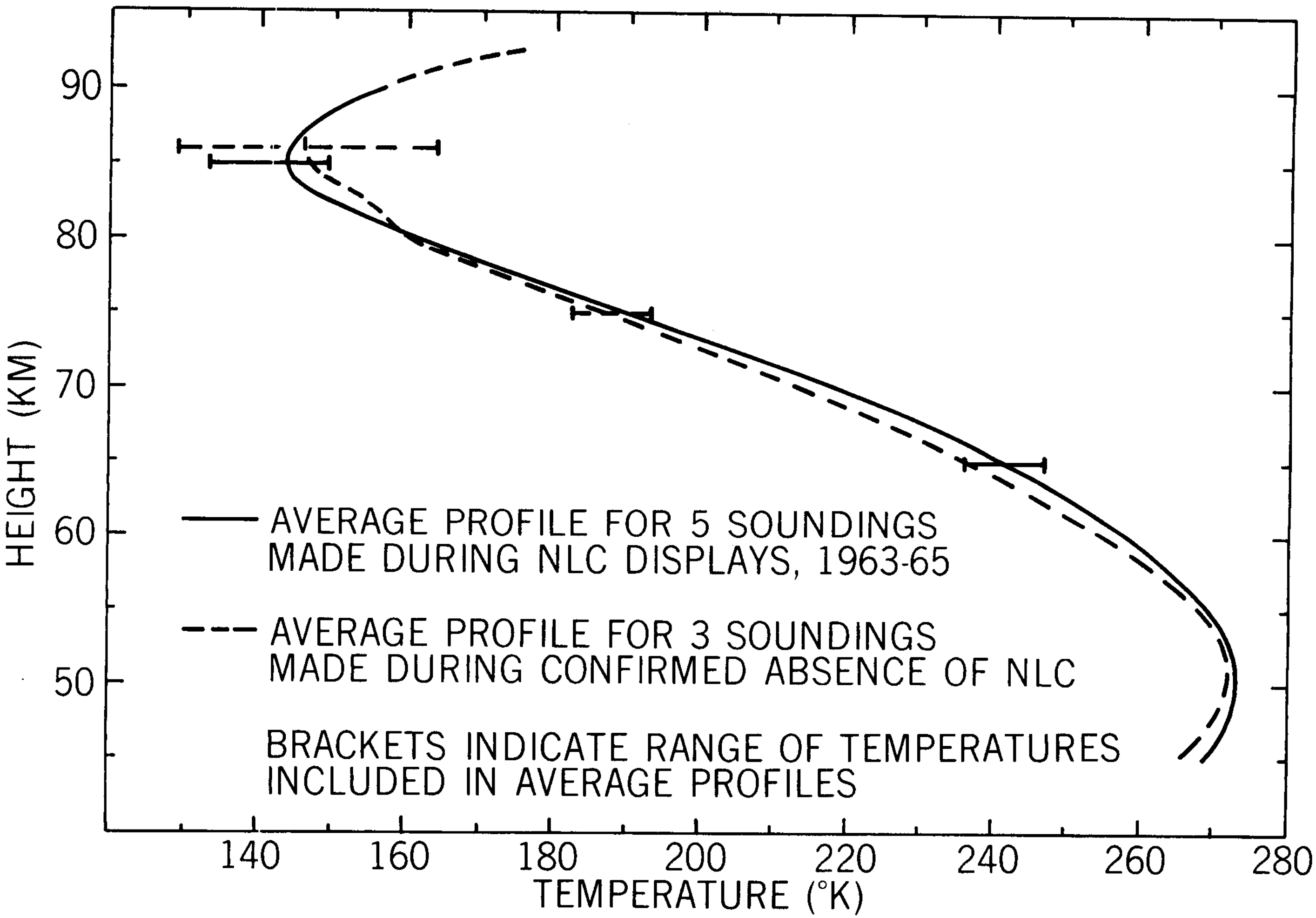

Figure 3. The average temperature profile for five soundings conducted during noctilucent cloud displays compared with the average temperature profile for three soundings conducted during the confirmed absence of the clouds. All eight soundings were made at Barrow and Kronogard during the summers 1963–1965.

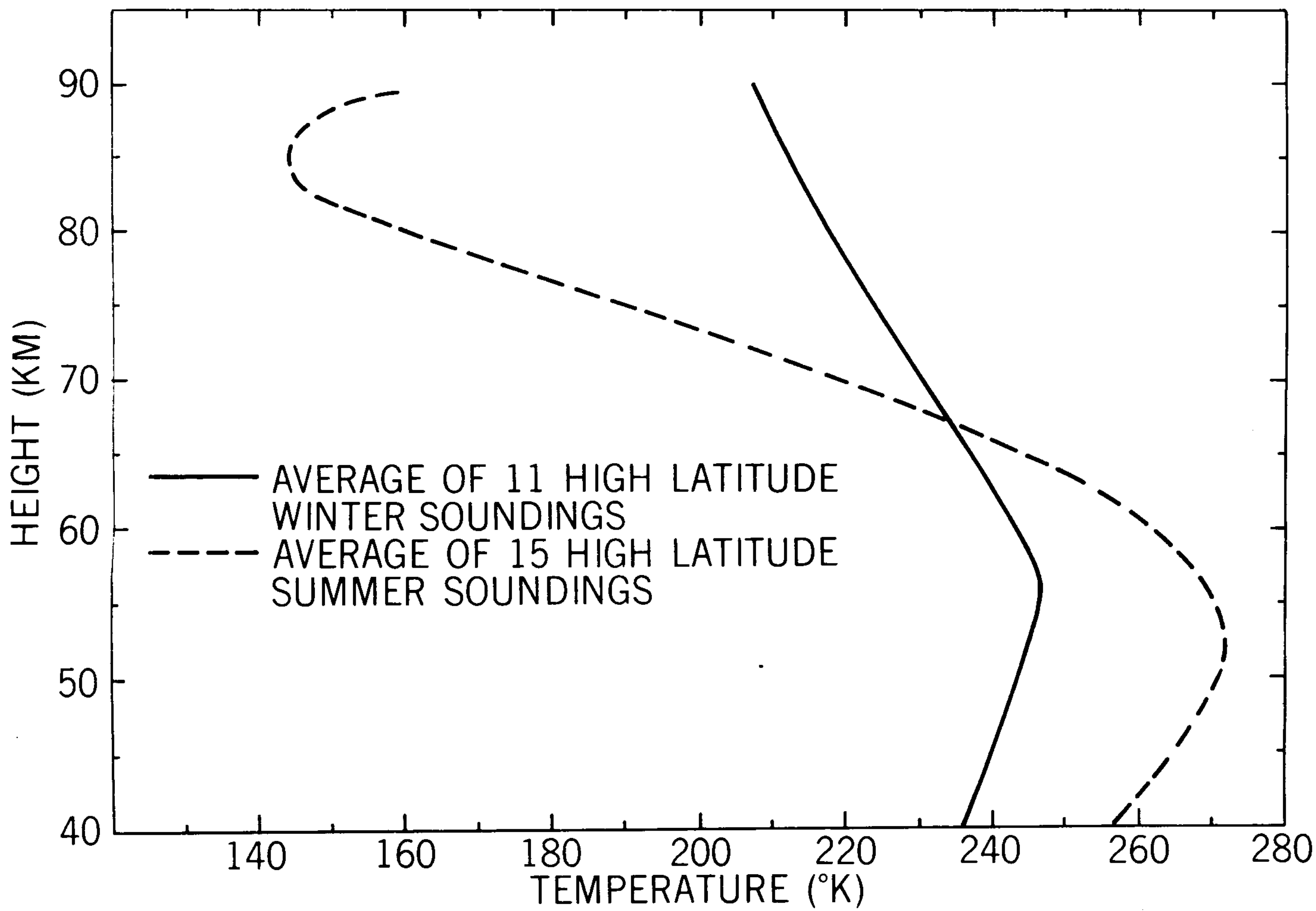

Figure 4. Typical high latitude summertime and wintertime temperature profiles. These averages include soundings from Churchill (59N), Barrow and Kronogard.

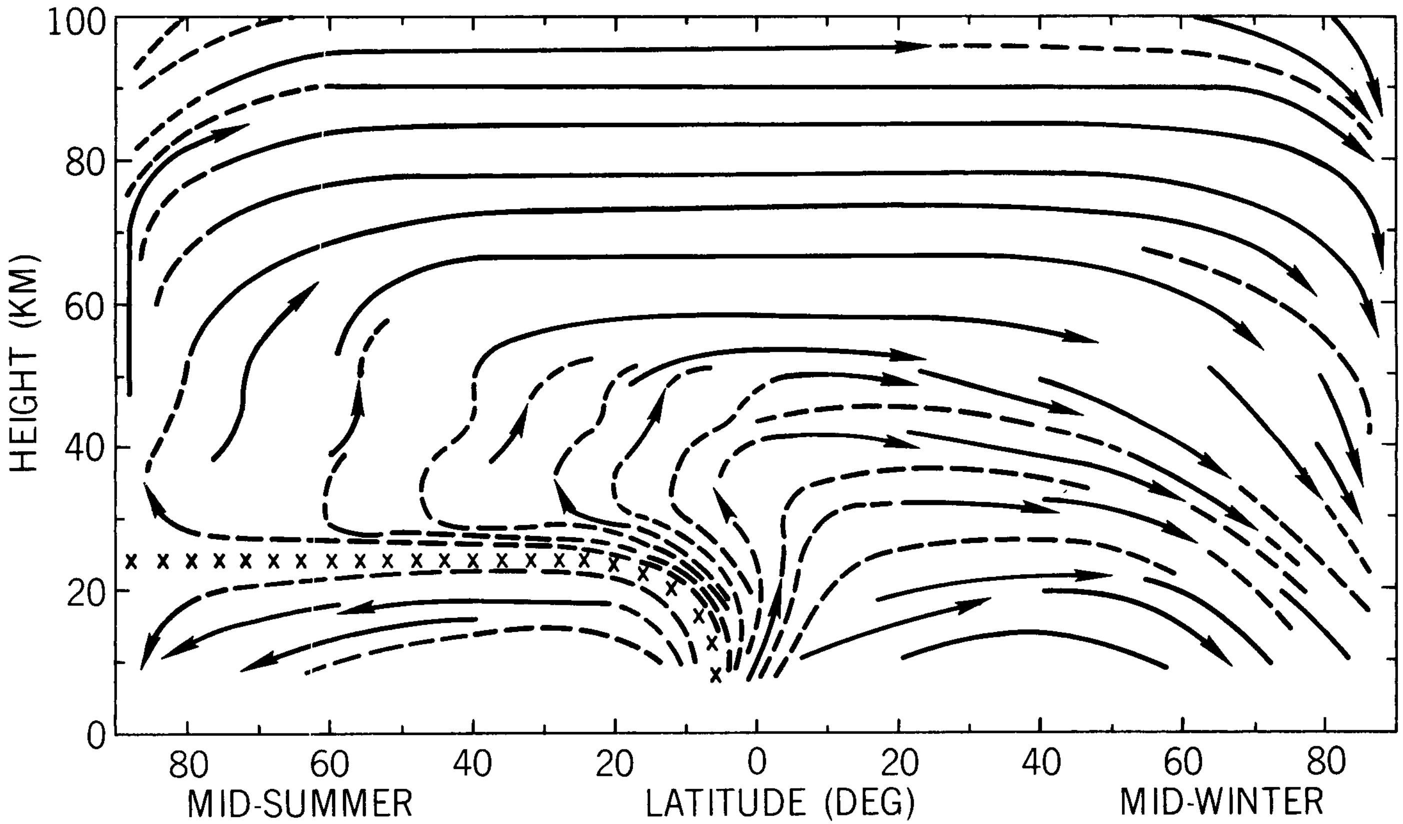

Figure 5. Meridional circulation after Hesstvedt.

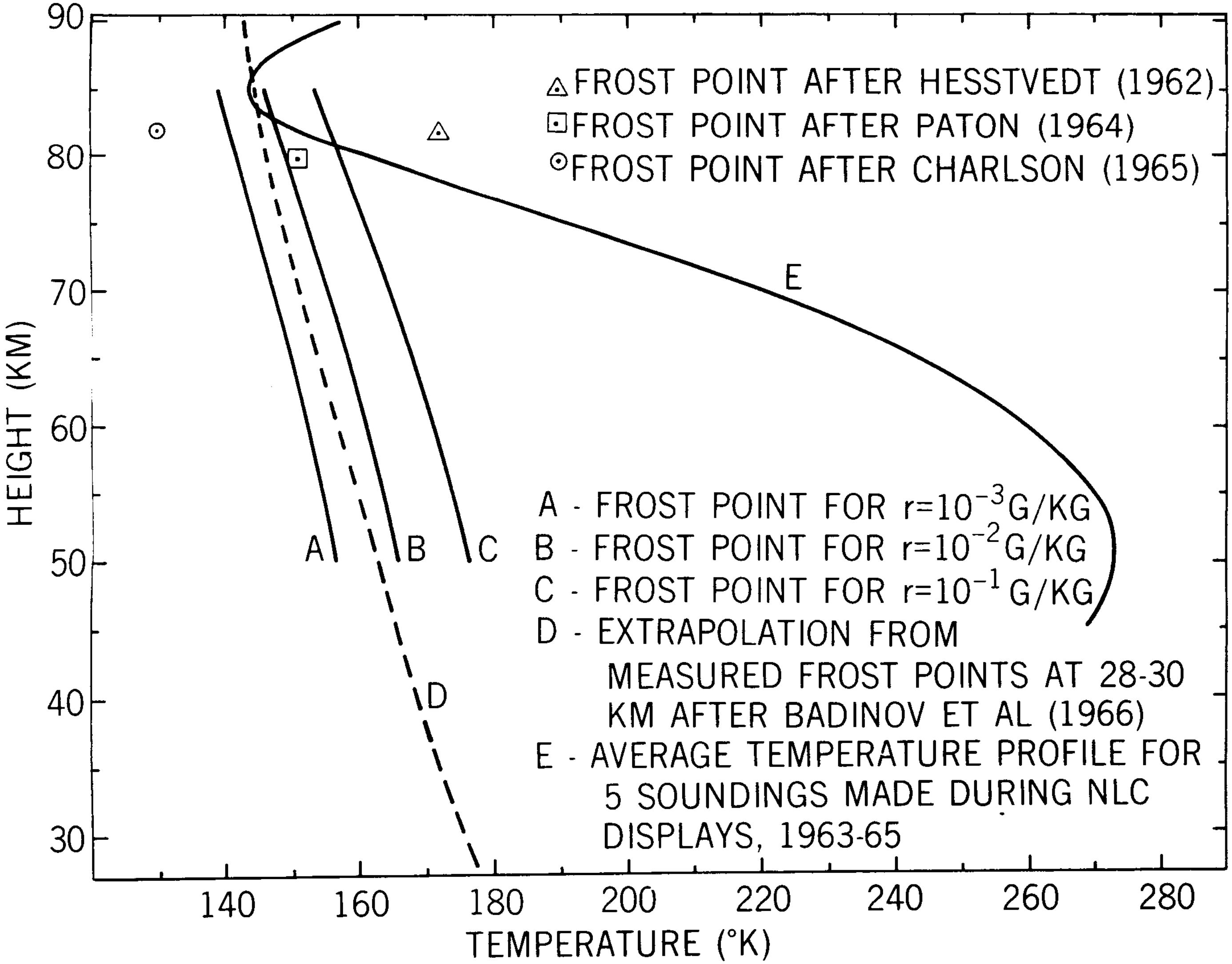

Figure 6. Comparison of frost point estimates by several authors with the average temperature profile for the five soundings conducted during noctilucent cloud displays.